Lifecycle Assessment of a Water Distribution System Pump

J. Nault, S.M.ASCE[1]; and F. Papa, M.ASCE[2]

Abstract: This article presents a methodology that combines a process-based lifecycle assessment (LCA) with an economic input-output LCA (EIO-LCA) model to quantify the net present value (NPV) lifecycle costs (LCC), energy consumption, and greenhouse gas (GHG) emissions associated with a water distribution system (WDS) pump. The methodology considers the manufacturing, use, and end-of-life (EOL) disposal lifecycle stages, as well as processes that are not typically considered, including discharge valve throttling, pump testing, deterioration, refurbishment, and variable-speed pumping. A case study is used to demonstrate the methodology, assess the implications of different operating scenarios, and determine the relative importance of different processes. Results show that a combination of refurbishment and variable-speed pumping is the most effective means of improving sustainability for the case. Analysis of the results shows similar composition profiles for energy consumption and GHG emissions with pump operation representing over 80% of each, whereas manufacturing and pump operation together represent the majority of the NPV LCC. Sensitivity analyses indicate that the planning period, reference target volume, electricity cost, and discount rate are the most influential parameters. **DOI: 10.1061/(ASCE)WR.1943-5452.0000546.**

Author keywords: Pumps; Sustainability; Water distribution systems; Energy consumption.

Introduction

Water distribution system (WDS) pumps, which convert electrical power into the hydraulic energy that allows treated water to overcome topological challenges and energy losses, are a key component of modern water supply infrastructure. It is common knowledge that WDS pumps consume large amounts of energy and often represent the largest component of a water utility's operating budget. For example, Burton (1996) showed that raw and treated water pumping can account for up to 95% of a water utility's energy use. Similarly, the Electric Power Research Institute (2002) suggests that more than 85% of the energy use in water supply operations is consumed by pumps alone. Many pumps are also oversized for their applications due to an emphasis on future demand conditions and consequently operate with throttled discharge valves. As a result, such pumps operate inefficiently and consume more energy than they otherwise need to. Additionally, pump performance deteriorates over time which results in increased energy consumption.

With regards to WDS pumps, many studies of WDS sustainability focus on pump operation with little-to-no consideration for other processes, namely manufacturing, maintenance, and end-of-life (EOL) disposal. Operating factors such as control via discharge valve throttling, pump deterioration, and refurbishment are rarely considered. A suitable approach to evaluating the sustainability of products and processes is lifecycle assessment (LCA), which entails evaluating the impacts of a product's or process' lifecycle stages. This article presents a methodology that combines a process-based LCA with Carnegie Mellon's (2014) economic input-output LCA (EIO-LCA) model to evaluate the sustainability of a WDS pump's lifecycle by quantifying its net present value (NPV) lifecycle costs (LCCs), energy consumption, and greenhouse gas (GHG) emissions.

The primary objective of this article is to present a methodology for quantifying the lifecycle costs and environmental implications of a WDS pump with consideration of lifecycle stages and operating practices that are not typically considered. These respectively include manufacturing and EOL disposal, and control via discharge valve throttling, refurbishment, variable-speed pumping, maintenance, and pump testing. An example WDS pump is used to demonstrate application of methodology; quantify the overall NPV LCC, energy consumption, and GHG emissions; evaluate the relative importance of different processes; and evaluate the impacts of different operational practices.

Background—WDS LCAs

Studies of WDS LCAs have traditionally focused on comparing different pipe materials, evaluating the sustainability of WDSs, and assessing future implications of present decisions. Dennison et al. (1999) used LCA to analyze the environmental impacts of ductile iron and medium density polyethylene pipes and found that manufacturing is the most energy-intensive process. Lundie et al. (2004) applied an LCA to Sydney Water's integrated water system to forecast the environmental implications of future water management decisions. An LCA approach complemented the planning process by quantifying the future impacts of present management decisions. Filion et al. (2004) studied the sustainability of WDSs by developing a methodology for quantifying the lifecycle energy of WDSs with consideration for pipe fabrication, replacement, and disposal, and pumping operations. This method combined a process-based LCA with Carnegie Mellon's (2014) EIO-LCA model. Similar to Filion et al. (2004), Stokes and Horvath (2006) used

[1]Graduate Student, Univ. of Toronto, 35 St. George St., Toronto, ON, Canada M5S 1A4 (corresponding author). E-mail: johnathan.nault@mail.utoronto.ca

[2]Principal, HydraTek and Associates, 204-216 Chrislea Rd., Woodbridge, ON, Canada L4L 8S5.

Note. This manuscript was submitted on August 1, 2014; approved on March 19, 2015; published online on May 5, 2015. Discussion period open until October 5, 2015; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Water Resources Planning and Management***, © ASCE, ISSN 0733-9496/A4015004(9)/$25.00.

LCA to evaluate the sustainability of alternative water supply frameworks. Racoviceanu et al. (2007) applied an LCA at a more local scale to analyze the operation of a water treatment plant (WTP). It was found that pumping accounted for more than 50% of the WTP's energy use and GHG emissions. Herstein et al. (2009) developed an index-based method that quantifies the environmental implications of WDSs. This method was applied to the design of a WDS and it was found that the feasible alternatives with the lowest environmental impact were also the most economical alternatives. Stokes and Horvath (2011) combined a process-based LCA and Carnegie Mellon's (2014) EIO-LCA model to quantify the lifecycle energy consumption and air emissions from water supply infrastructure. It was demonstrated that the lack of a lifecycle perspective can lead to underestimating energy and emissions impacts. Similar to Dennison et al. (1999), Du et al. (2013) also used LCA to compare materials for water and wastewater pipes. In all of the studies above, LCA has provided valuable insight by considering the processes throughout the lifecycle of WDSs.

Early optimization studies of WDSs focused on the single objective of minimizing capital and operational costs. For example, some studies focused on minimizing costs by optimizing pumping operations (e.g., Ormsbee et al. 1989; Brion and Mays 1991; and Ormsbee and Lansey 1994). However, it is now more prudent to consider multiple objectives and strive for sustainable designs. Recent studies have formulated the WDS optimization problem in terms of minimizing lifecycle costs, GHG emissions, and energy and resource consumption while maximizing water quality and resilience. Dandy et al. (2008) formulated the problem in terms of the sustainability objectives of minimizing lifecycle costs, energy consumption, GHG emissions, and resource consumption. Wu et al. (2010b) also investigated the implications of using single-objective optimization versus multiobjective optimization to minimize a WDS's costs and GHG emissions, whereby the single-objective approach uses carbon pricing to represent GHG emissions as a cost. Wu et al. (2013) used mutliobjective approach to optimize WDS operation with consideration for lifecycle energy consumption, costs, GHG emissions, and hydraulic capacity. In addition to identifying sustainable network designs, some studies have also used multiobjective optimization to investigate tradeoff relationships between objectives. Wu et al. (2010a) used multiobjective optimization to study the trade-offs between minimizing lifecycle costs and GHG emissions, whereas Ostfeld et al. (2013) investigated the trade-off relationship between costs and reliability for optimal network design. Both Kurek and Ostfeld (2013) and Mala-Jetmarova et al. (2014) investigated the trade-off relationship between pumping costs and water quality; the former found that lower pumping costs cannot be achieved without decreased water quality, whereas the latter also incorporated storage-reliability requirements.

It is apparent from the aforementioned studies that it is now commonplace to consider multiple objectives that represent different aspects of sustainability. While a systems-based perspective of WDSs is important, it is also important to analyze the sustainability of individual components while considering local factors. For example, few studies have considered the cost, energy, and GHG emission implications of pump deterioration and the benefits of refurbishment. Pascual et al. (2011) studied the strategic refurbishment of pumps, whereas Richardson and Hodkiewicz (2011) used mutliobjective optimization to minimize the lifecycle costs and GHG emissions associated with pumping operations by optimizing refurbishment schedules. Both of these studies showed that refurbishment can reduce costs, energy consumption, and GHG emissions. The present study supplements gaps in the literature by providing a means of quantifying the NPV LCC, energy consumption, and GHG emissions of individual pumps with consideration for discharge valve throttling, deterioration, refurbishment, and variable-speed pumping.

Methodology for Performing LCA of a WDS Pump

The methodology, which combines a process-based LCA with Carnegie Mellon's (2014) EIO-LCA model, is presented in three subsections. First, the functional unit and sustainability measures that represent a WDS pump's performance objectives are presented. Next, the scope of the study is described in terms of the system boundaries and lifecycle stages. Lastly, details are provided regarding calculating the sustainability measures for each lifecycle stage.

Functional Unit and Sustainability Measures

The primary function of water treatment and distribution operations is to provide potable water; therefore, the functional unit for this study is the gross volume of water pumped over the planning period, measured in $10^6\ m^3$. The sustainability measures of interest are NPV LCC, measured in dollars ($); gross energy consumption, measured in GWh; and GHG emissions produced, measured in t-CO_2-eq. Energy consumption is a suitable measure for the sustainability of WDS pumps because: they consume large amounts of energy in their use stage; energy does not appreciate or depreciate over time; it is not influenced inflation; and, as noted by Filion et al. (2004), energy consumption is representative of resource consumption and waste generation (i.e., greater energy consumption results in greater extraction and consumption of natural resources, such as coal and nuclear fuel, which are accompanied by increased waste generation and emissions). The NPV LCC and GHG emissions supplement the analysis by providing an additional perspective on the financial implications and global warming potential associated with a WDS pump.

In addition to the sustainability measures, three performance metrics are used to describe the performance of a WDS pump. These comprise the pump energy indicator (PEI), energy efficiency indicator (EEI), and average utilization. Because pumps provide both flow and head, it is prudent to supplement the analysis with a measure that represents both of these functions. HydraTek's (2013) PEI was shown to provide a better representation of performance than an indicator based solely on volume. The EEI metric represents overall lifecycle energy efficiency. It is calculated as the quotient of the gross energy delivered (GED), which represents the actual energy delivered to a WDS after the discharge valve over the course of the planning period, and total energy consumption. A greater EEI value implies that a WDS pump has greater overall lifecycle energy efficiency. Lastly, utilization represents an owner's reliance on a pump and with greater reliance comes greater risk as well as greater deterioration.

Lifecycle Stages and System Boundaries

The lifecycle stages of a WDS pump considered within this study are the fabrication, use, and EOL stages. These stages, their processes, and the energy and GHG emission fluxes are shown in Fig. 1. While not shown, costs fluxes have the same flow as the energy fluxes.

As shown in Fig. 1, the decommissioning, disposal via landfilling, and component reuse processes are excluded from this study. This is because decommissioning is often included within other capital projects, the bulk of a WDS pump is presumed to consist of recyclable metal, and component reuse is uncommon and infrequent.

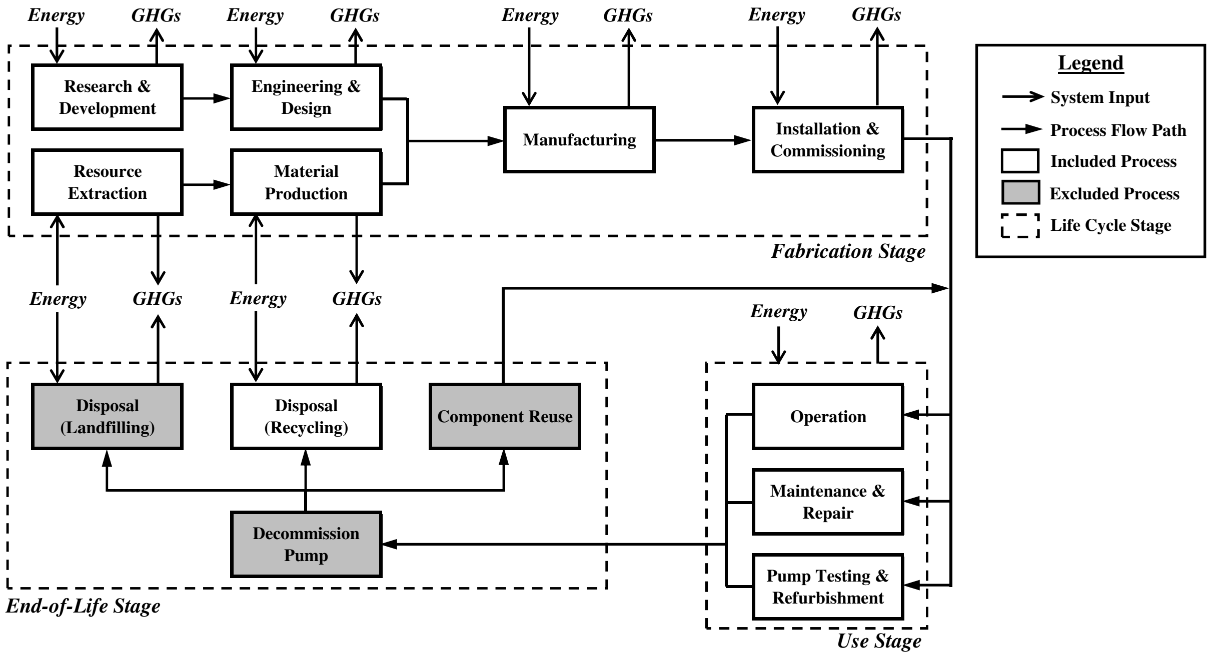


Fig. 1. Lifecycle stages, processes, and system boundaries of a WDS pump

Model Development

Lifecycle Costs, Energy Consumption, and GHG Emissions

The sustainability measures each have components that correspond to the three lifecycle stages and are calculated as follows:

$$C_{\text{total}} = C_{\text{fab}} + C_{\text{use}} + C_{\text{EOL}} \tag{1}$$

$$E_{\text{total}} = E_{\text{fab}} + E_{\text{use}} + E_{\text{EOL}} \tag{2}$$

$$G_{\text{total}} = G_{\text{fab}} + G_{\text{use}} + G_{\text{EOL}} \tag{3}$$

where C is the NPV cost ($); E is the energy consumption (GWh); G is the GHG emissions produced (t-CO_2-eq); and the subscripts refer to the total sustainability measures and respective lifecycle stages. Because monetary values appreciate with time, each term within Eq. (1) represents a present value cost.

Fabrication Stage

The environmental implications associated with WDS pump manufacturing are difficult to estimate due to the myriad activities involved. Therefore, similar to Filion et al. (2004) and Stokes and Horvath (2011), Carnegie Mellon's (2014) EIO-LCA model is used to estimate the energy consumption and GHG emissions associated with a WDS pump's fabrication by using the pump's capital cost. In doing this, it is assumed that the purchase cost of a pump is representative of the fabrication environmental implications. The energy and GHG emissions measures for the fabrication stage are respectively calculated as

$$E_{\text{fab}} = e_{\text{fab,pump}} C_{c,\text{pump}} + e_{f\text{ab,VSD}} C_{c,\text{VSD}} \tag{4}$$

$$G_{\text{fab}} = g_{\text{fab,pump}} C_{c,\text{pump}} + g_{f\text{ab,VSD}} C_{c,\text{VSD}} \tag{5}$$

where e_{fab} is the fabrication-energy conversion factor (GWh/$); g_{fab} is the fabrication-emissions conversion factor (t-CO_2-eq/$); and C_c is the capital cost ($). The subscripts pump and VSD refer to those values for the pump and the variable-speed drive, respectively. The conversion factors are discussed within the "Conversion Factors" section.

Use Stage

Within the use stage, the sustainability measures are primarily attributed to pump operation; however, maintenance, pump testing, and refurbishment also contribute. Maintenance includes frequent activities such as re-lubricating bearings and checking for excessive vibrations, while refurbishment involves fully dismantling a pump and restoring it to near-new condition. The sustainability measures for the use stage are calculated as

$$C_{\text{use}} = C_{\text{op}} + C_{\text{maint}} + C_{\text{test}} + C_{\text{ref}} \tag{6}$$

$$E_{\text{use}} = E_{\text{op}} + e_{\text{lab}}((f_{\text{maint}} c_{\text{maint}} + f_{\text{test}} c_{\text{test}})T + c_{\text{ref}} N_{\text{ref}} + C_{\text{VSD}}) \tag{7}$$

$$G_{\text{use}} = G_{\text{op}} + g_{\text{lab}}((f_{\text{maint}} c_{\text{maint}} + f_{\text{test}} c_{\text{test}})T + c_{\text{ref}} N_{\text{ref}} + C_{\text{VSD}}) \tag{8}$$

where C_{op}, C_{maint}, C_{test}, and C_{ref}, are the present value costs of operation, maintenance, testing, and refurbishment ($), respectively; E_{op} is the operational energy consumption (GWh); G_{op} is the operational GHG emissions (t-eq-CO_2); e_{lab} is a labor-energy conversion factor (GWh/$); g_{lab} is a labor-GHG emissions conversion factor (t-CO_2-eq); c_{maint} is the maintenance cost rate ($/h); c_{test} is the pump test cost rate ($/test); f_{maint} is the annual labor-hours (h/year); f_{test} is the testing frequency (tests/year); c_{ref} is the refurbishment cost rate ($); N_{ref} is the number of refurbishments during the planning period; and T is the planning period (years).

The operational measures depend on a pump's operating point over time. The operating point itself depends on the pump head curve, which deteriorates over time, and the system characteristics, which include the hydraulic implications of discharge valve throttling. One means of determining the operating point over time is through the use of a hydraulic model; however, for systems where water transmission is largely separated from distribution

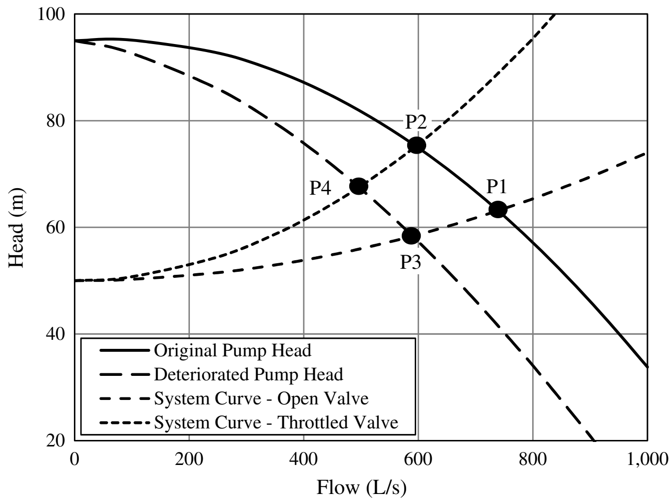


Fig. 2. Example pump and system curves showing the range of potential operating points

operations, a simpler alternative that requires less data is to calculate the intersection of the pump head curve and system curve as illustrated in Fig. 2.

Within Fig. 2, point P1 represents the operating point of a new pump with an open discharge valve; conversely, point P4 represents the operating point of a deteriorated pump with a throttled discharge valve. Discharge valve throttling is commonly used to control the operating point but results in increased operating time, faster deterioration, and therefore greater energy consumption.

Regarding deterioration, the model presented by Richardson and Hodkiewicz (2011) is used here. Richardson and Hodkiewicz suggest that the two primary mechanisms of pump deterioration are internal flow recirculation and internal roughness development, which agrees with Beebe (2004). The deteriorated head and power for a variable-speed pump are respectively calculated as

$$H_p' = \omega^2\left(a\left(\frac{Q+R}{\omega}\right)^2 + b\left(\frac{Q+R}{\omega}\right) + c - K_T t\left(\frac{Q}{\omega}\right)^2\right) \quad (9)$$

$$P_p' = \omega^3\left(d\left(\frac{Q+R}{\omega}\right)^3 + e\left(\frac{Q+R}{\omega}\right)^2 + f\left(\frac{Q+R}{\omega}\right) + g\right) \quad (10)$$

where H_p' is the effective pump head (m); P_p' is the effective pump power (kW); Q is the system flow (L/s); R is the pump's internal flow recirculation (L/s); K_T is an internal roughness development factor (m-s^2/L^2-h); t is the cumulative operating time (h); ω is the relative speed; and the characters a through g are pump curve coefficients. The effective pump head is the net head provided by a pump, and the effective power is the actual power consumption. Internal flow recirculation varies with a pump's head and is calculated as

$$R = 2\gamma D H_p^{0.5}\left(\sqrt{\frac{c^3}{75\times c + L}} - \sqrt{\frac{c_o^3}{75\times c_0 + L}}\right) \quad (11)$$

$$c = c_o \times \ln(\beta t + e) \quad (12)$$

where $\gamma = 9.84\times 10^{-2}$ m$^{1.5}$/mm-s; D is the wear ring diameter (mm); H_p is the original pump head (m) at flow Q; c is the wear ring clearance (mm); c_0 is the initial wear ring clearance (mm); L is the axial length of the wear ring (mm); β is a wear ring deterioration parameter (h^{-1}); and e is Euler's number. When compared to the deterioration model used by Pascual et al. (2011), this model is advantageous in that it considers the deterioration of both performance and power consumption; however, it does not consider the impacts of operating near run-out conditions or with cavitation which would increase the rate of deterioration. To the authors' knowledge, there are no reference values available for the deterioration parameters β and K_T; however, if field data are available, they can be determined via calibration.

End-of-Life Stage

The sole process of the EOL stage considered within this study is disposal via recycling. A WDS pump reaches its EOL when it has deteriorated too much, requires excessive maintenance, or is no longer suited to a system. EOL energy consumption and GHG emissions are respectively calculated as

$$E_{\text{EOL}} = e_{\text{rec}} W \quad (13)$$

$$G_{\text{EOL}} = g_{\text{rec}} E_{\text{EOL}} \quad (14)$$

where e_{rec} is a recycling-energy conversion factor (GWh/t); g_{rec} is a GHG emissions-energy conversion factor (t-CO_2-eq/GWh); and W is the bulk weight of the WD pump (t). EOL costs are assumed to be relatively small and included within other capital projects.

Conversion Factors

Conversion factors are used to calculate the impact of processes or components thereof. The values of the conversion factors are provided in Table 1.

The conversion factors used within Eqs. (4), (5), (7), and (8) were obtained from Carnegie Mellon's (2014) EIO-LCA US 2002 Purchaser model. By using matrices that represent the flow, consumption, and interaction of material, energy, emissions, monetary, and other values across various industries that result from economic activity, the EIO-LCA model can be used to compute the consequences of different processes. While the EIO-LCA model is linear and therefore does not consider economies of scale, it quantifies economy-wide environmental impacts across various industries (Herstein et al. 2009). The WDS pump fabrication conversion factors were obtained from the pump and pumping equipment manufacturing sector, the labor conversion factors were obtained from the all other services miscellaneous professional and technical services sector, and the variable-speed drive fabrication conversion factors were obtained from the switchgear and switchboard apparatus manufacturing sector. The recycling conversion factors are referenced from Johnson et al. (2008) for recycled austenitic stainless steel which is assumed to be comparable to the composition of a WDS pump. Lastly, the energy-emissions conversion

Table 1. Conversion Factors

Parameter	Value
$e_{\text{fab,pump}}$ (kWh/$)	2.2
$g_{\text{fab,pump}}$ (kg-CO_2-eq/$)	0.53
$e_{\text{fab,VSD}}$ (kWh/$)	1.7
$g_{\text{fab,VSD}}$ (kg-CO_2-eq/$)	0.40
e_{lab} (kWh/$)	0.51
g_{lab} (kg-CO_2-eq/$)	0.12
g_{elec} (kg-CO_2-eq/MWh)	170
e_{rec} (MWh/ton)	7.2
g_{rec} (kg-CO_2-eq/t)	5,320

factor, which represents the emissions associated with power generation, was obtained from Environment Canada (2011).

Case Study: WDS Pump in Southern Ontario

System Description

The example presented here is based on a high lift pump at a water treatment plant in Southern Ontario with some data having been modified for simplicity. Additionally, the parameters' values are assumed to be constant throughout the planning period. The pump was installed in 1997 and a performance test was conducted in 2013. According to field data, the pump is typically operated on its own; because of this, the operating point is modeled using pump and system curves with the assumption that the system will not change significantly over the planning period. The purpose of this example is to demonstrate the methodology presented above; assess the NPV LCC, energy, and GHG emissions implications of different operating scenarios; and determine the relative importance of each process. Table 2 summarizes the pump's original properties.

Fig. 3 provides the pump's original and deteriorated head and efficiency curves after a run time of approximately 8,000 h, as well as the system curve. The curves representing the deteriorated state have been calibrated with the aforementioned test data. Fig. 3 shows that the pump's performance has deteriorated significantly with a loss of 14% at the best efficiency point and a moderate shift in the head curve. System curve properties and annual pumped volume were estimated using field data; these are described in the model parameters section.

Eleven operating scenarios are evaluated for the WDS pump. The details of each scenario summarized in Table 3. Scenario 1 represents the base case, while the remaining scenarios represent a combination of operating practices. Valve positions of 75% open and 50% open were selected to shift the operating point to within the vicinity of the pump's best efficiency point. Pump refurbishments are evenly distributed throughout the planning period, and scenarios with a relative speed less than unity include the installation of a variable-speed drive (VSD). With regards to refurbishments, it is assumed that the original clearances are fully restored. It should be noted that because the objective of this article is not one of optimization, only a limited number of scenarios with discrete values are explored.

Model Parameters

The values of the parameters used to model the pump, system, and operating conditions are presented below. Uncertain parameters that strongly influence the results are subjected to a sensitivity analysis.

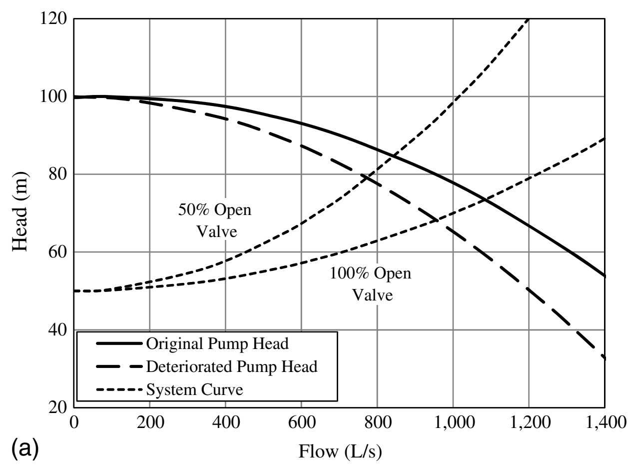
Pump and Drive Characteristics

Parameters describing the pump comprise head and power curve coefficients, dimensions, and deterioration parameters. The pump head and power curves are modeled using Eqs. (9) and (10), respectively, and the parameters for these equations are provided in Table 4.

The pump's dimensions and weight are referenced from manufacturer data for a similar pump (Flowserve 2013) and are listed in Table 5. The deterioration parameters provided in Table 4 were determined by calibrating the deterioration model to data from the 2013 field test.

Table 2. Summary of Original Pump Properties

Property	Value
Rated flow (L/s)	860
Rated head (m)	84.0
Rated power (kW)	810
Peak efficiency	87.3%
Impeller diameter (mm)	870
Capital cost	$2 million



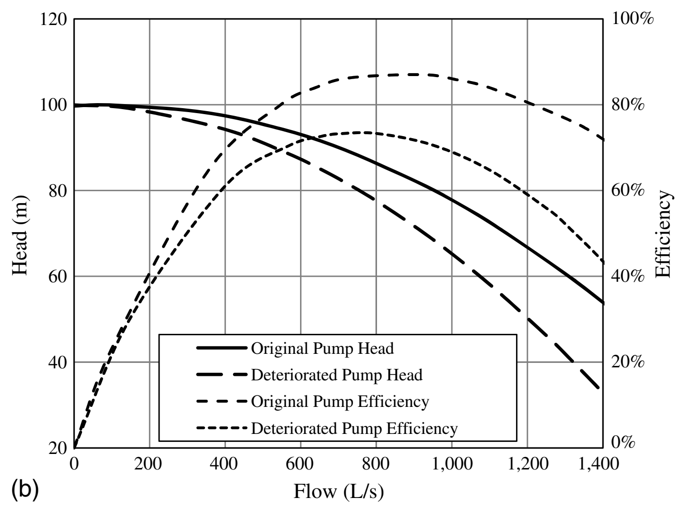


Fig. 3. Original and deteriorated pump curves and system curve: (a) pump performance and system curves; (b) pump performance and efficiency curves

Table 3. Operating Scenario Details

Scenario	Valve position (%)	Number of refurbishments	Relative pump speed
1	100	0	1.00
2	75	0	1.00
3	50	0	1.00
4	100	1	1.00
5	100	2	1.00
6	100	0	0.90
7	100	0	0.80
8	100	1	0.90
9	100	1	0.80
10	100	2	0.90
11	100	2	0.80

Table 4. Pump Performance and Power Curve Parameters

Coefficient	Value
a	-2.7×10^{-5}
b	5.1×10^{-3}
c	1.0×10^{2}
d	-2.6×10^{-7}
e	5.2×10^{-4}
f	2.3×10^{-1}
g	3.9×10^{2}

Table 5. Pump Dimensions, Weight, and Deterioration Parameters

Parameter	Value
D (mm)	500
L (mm)	45
c_0 (mm)	0.35
W (t)	1.0
β (h^{-1})	5.0×10^{-3}
K_T (m-s^2/L^2-h)	1.0×10^{-9}

Lastly, a nominal motor efficiency of 95% and VSD efficiency of 97% were selected, which are typical of motors and drives used with WDS pumps.

System Characteristics

System parameters represent the system curve, annual target volume, target volume growth rate, and the planning period. The system curve, which includes the hydraulic implications of the discharge valve, is modeled as

$$H_{\text{sys}} = \left(a_{\text{sys}} + \frac{1}{\tau'^2 E^2}\right) Q^2 + b_{\text{sys}} \tag{15}$$

where a_{sys} is the dynamic system coefficient (m-s^2/L^2); b_{sys} is the system's static head (m); τ' is the effective valve opening; and E is the valve's conductance (L/s-m$^{0.5}$). The values of these parameters, along with the reference target volume TV_0, its growth rate i_{TV}, and the planning period T, are provided in Table 6.

The valve's τ'-curve is modeled using a quadratic closure curve that is representative of reference data for butterfly valves (Siemens 2013; ValMatic 1999). The reference target volume is the target volume for the first year within the planning period. A target volume growth rate of 1.4%/year coincides with the present population growth rate for the Greater Toronto Area of Ontario (Ontario Ministry of Finance 2013). Lastly, a planning period of 40 years was selected, which is assumed to be a reasonable value given the ages of other WDS pumps in Ontario (HydraTek & Associates 2013).

Cost Rates and Maintenance and Testing Frequencies

Lastly, cost rates and maintenance and testing frequencies are used with the operational model and Eq. (6) to calculate components of the lifecycle costs. The values of these parameters are provided in Table 7.

An annual discount rate of 5% is assumed to be representative of long-term average market conditions; however, because economic conditions can be highly volatile, this parameter is included within the sensitivity analysis. An electricity cost of \$0.13/kWh was selected as a representative value for large energy consumers in Southern Ontario. The testing frequency is based on that recommended in HydraTek's (2013) report for a pump with a rated power of 810 kW and utilization rate of 15%, while the testing and refurbishment costs are based on personal communications with HydraTek.

Table 6. System and Valve Characteristics

Parameter	Value
a_{sys} (m-s^2/L^2)	2.0×10^{-5}
b_{sys} (m)	45
TV_0 (ML/y)	3,000
i_{TV} (%/y)	1.4
T (y)	40
E (L/s-m$^{0.5}$)	500

Table 7. Cost Rates and Maintenance and Testing Frequencies

Parameter	Value
i (%/year)	5
c_{elec} (\$/kWh)	0.13
c_{ref} (\$/refurb.)	64,000
c_{VSD} (\$/unit)	300,000
c_{test} (\$/test)	2,500
c_{lab} (\$/h)	100
C_c (\$)	2,000,000
f_{maint} (h/year)	250
f_{test} (tests/year)	0.1

Results

Results, which comprise the sustainability measures and performance metrics for each scenario, are respectively provided in Tables 8 and 9. Additionally, pump utilizations over the planning period for select scenarios are illustrated in Fig. 4.

Recalling that lower values for all three sustainability measure are desirable, the results in Table 8 show that scenarios 2 and 3, which involve throttling the discharge valve to 75% open and 50% open, respectively, have the highest NPV LCC, energy consumption, and GHG emissions and are therefore the least sustainable scenarios. The pump utilization profile for scenario 3 in Fig. 4 also shows increased utilization relative to scenario 1. These imply that discharge valve throttling is an inefficient means of controlling the operating point from cost, energy, and GHG emissions perspectives. Despite this, the PEI metrics in Table 9 suggest that these scenarios are slightly more efficient than scenario 1. However, because the PEI metric does not reflect the energy losses associated with the throttled valve, it is an incomplete metric in this context (in that it is meant to characterize the pump only, and not the effect of system components). The results in Table 9 and Fig. 4 also

Table 8. Results for Sustainability Measures

Scenario	C_{total} (\$1,000)	E_{total} (GWh)	G_{total} (t-CO_2-eq)
1	4,910	52.8	9,320
2	4,970	53.9	9,510
3	5,150	57.3	10,090
4	4,840	49.8	8,820
5	4,820	48.7	8,630
6	4,970	49.0	8,700
7	4,790	46.2	8,230
8	4,890	45.8	8,160
9	4,680	42.1	7,540
10	4,870	44.6	7,960
11	4,650	40.6	7,280

Table 9. Results for Performance Metrics

Scenario	Average PEI (kWh/Mm^3-m)	GED (GWh)	EEI	Average utilization
1	4,470	26.1	0.493	0.149
2	4,420	25.5	0.473	0.155
3	4,360	24.2	0.421	0.176
4	4,000	27.3	0.548	0.135
5	3,810	27.9	0.572	0.130
6	4,430	23.5	0.479	0.193
7	4,620	21.3	0.462	0.291
8	3,960	24.4	0.532	0.171
9	4,080	21.9	0.519	0.250
10	3,770	24.8	0.556	0.164
11	3,860	22.1	0.545	0.235

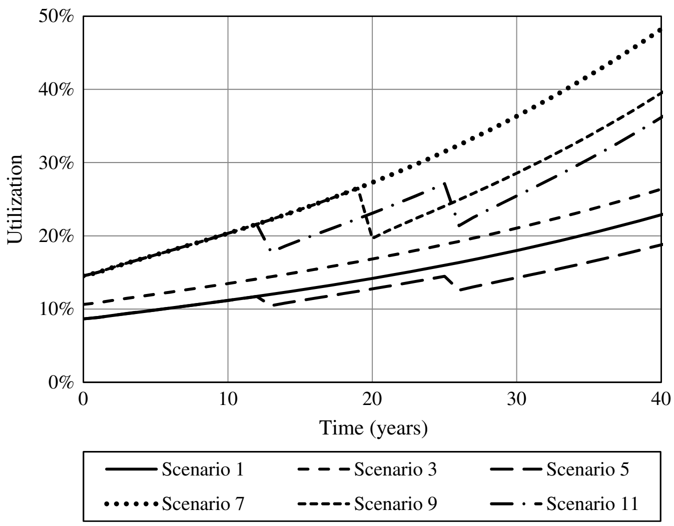


Fig. 4. Pump utilization over the planning period for select scenarios

show that discharge valve throttling increases utilization, which accelerates deterioration and decreases the actual energy provided to the WDS.

Regarding refurbishment, the results in Table 8 for scenarios 4 and 5 show that one and two refurbishments during the planning period improve the overall sustainability of the WDS pump. The results in Table 9 show a decrease in PEI and increase in GED, while the curve for scenario 5 in Fig. 4 shows decreased utilization relative to scenario 1. These respectively signify that refurbishment improves operating efficiency, increases the energy delivered to the WDS, and decreases reliance on the pump. Scenarios 4 and 5 also have the greatest EEI which indicates an increase in lifecycle energy efficiency.

Results for scenarios 6 and 7 show that decreasing the pump's speed leads to decreased energy consumption and GHG emissions, although not necessarily decreased costs. From Table 8, the NPV LCC for scenario 6 is greater than that of scenario 1, while the NPV LCC for scenario 7 is less than that of scenario 1. It is also of interest to note that the decrease in speed is accompanied by a large increase in utilization, which can be seen for the curve for scenario 7 in Fig. 4, and therefore greater wear on the pump.

Overall, the results for scenarios 9 and 11 show that a combination of refurbishment and variable-speed pumping greatly improves the WDS pump's sustainability. In particular, the results

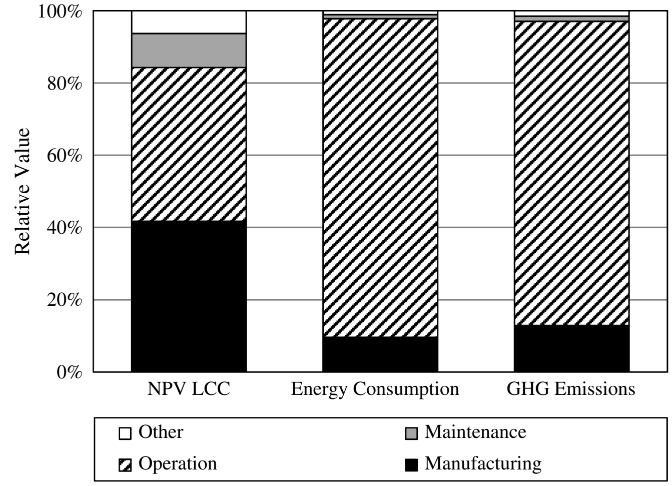


Fig. 5. Sustainability measure profiles for scenario 11

for scenario 11 show decreases in the NPV LCC, energy consumption, and GHG emissions of 5.3, 23.1, and 21.9%, respectively, relative to scenario 1.

In addition to investigating the impact of different operating practices, it is also of interest to investigate the sustainability measures' composition to ascertain the relative importance of each process. For example, consider the sustainability measure profiles for scenario 11 in Fig. 5. Fig. 5 shows that the profiles for energy consumption and GHG emissions are relatively similar while that of the NPV LCC, which has a greater weighting of pump manufacturing, is quite different. This difference can be attributed to the effect of the time value of money on capital and operating costs. Pump operation represents a large component of each measure at 39.6, 86.4, and 81.9% of the WDS pump's NPV LCC, energy consumption, and GHG emissions, respectively. Maintenance also represents a moderate component of the NPV LCC. Fig. 5 also shows that the other processes, which include refurbishment, testing, the VSD, and disposal, represent 7.7, 1.4, and 1.9% of the NPV LCC, energy consumption, and GHG emissions.

Sensitivity to Select Parameters

A sensitivity analysis was performed to assess the sensitivity of uncertain and influential parameters. The sensitivity analysis was completed by adjusting individual parameters for scenario 11 from 75 to 125% of their base values and computing the corresponding relative changes in the NPV LCC and energy consumption sustainability measures. The GHG emissions measure is not included here because it was shown to have a similar profile to energy consumption for scenario 11 and is therefore assumed to have similar sensitivities. The parameters selected for testing are the planning period; reference target volume; target volume growth rate; present value discount rate; electricity cost; pump fabrication-energy conversion factor; and labor cost rate. Other uncertain parameters (i.e., those representing pump testing, refurbishment, and disposal) are not tested since it was shown in Fig. 4 that the *other* category of processes constitutes a relatively small portion of the sustainability measures. Sensitivity plots for the relative changes in present value cost and energy consumption are provided in Fig. 6.

Of the parameters tested, Fig. 6 shows that the planning period, reference target volume, electricity cost, and discount rate are the most sensitive, while the target volume growth rate and labor cost rate are relatively insensitive. Specifically, Fig. 6(a) shows that the

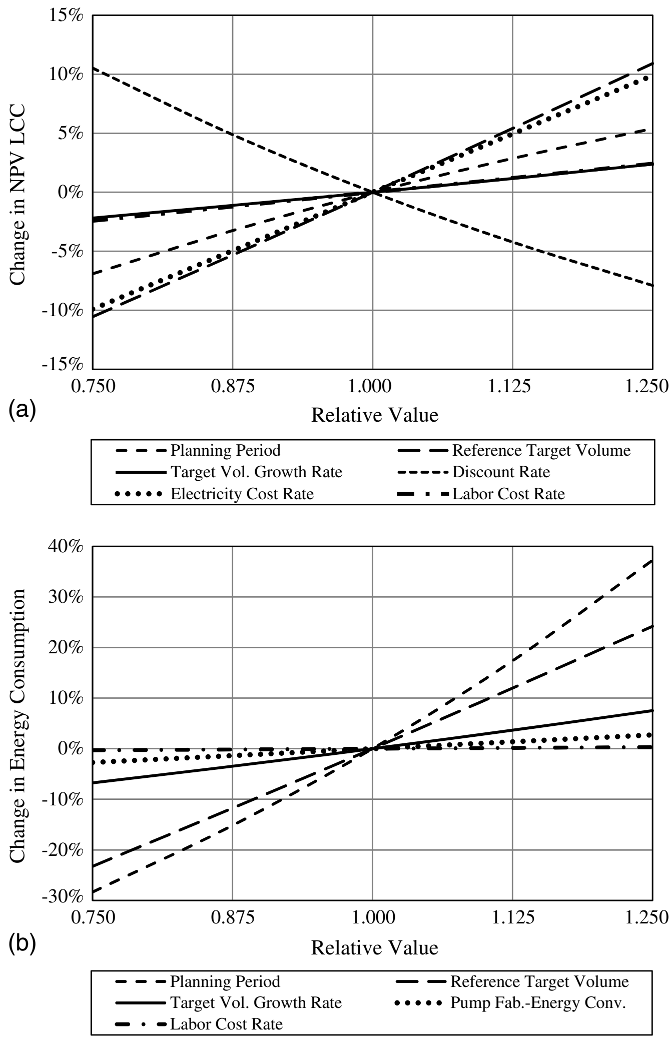


Fig. 6. Sensitivity plots for select parameters: (a) NPV LCC; (b) energy consumption

NPV LCC is only moderately sensitive to the discount rate, reference target volume, and electricity cost, while Fig. 6(b) shows that energy consumption is highly to the planning period and reference target volume.

Conclusions and Broader Implications

This article presented a methodology that uses a process-based LCA with Carnegie Mellon's (2014) EIO-LCA model to quantify the NPV LCC, energy consumption, and GHG emissions of a WDS pump's lifecycle with consideration for processes that are not commonly considered. The EIO-LCA model was used to calculate cost, energy, and GHG emissions quantities, while a calibrated deterioration model was used to incorporate the effects of pump deterioration. An example WDS pump was used to demonstrate the methodology for multiple scenarios and explore the composition of the sustainability measures. Additionally, a sensitivity analysis was performed to evaluate the sensitivity of the methodology's results to uncertain and influential parameters. Like other LCA studies but within the context of WDS pumps, this article highlights the importance of considering multiple aspects of sustainability, as well as multiple performance measures, since consideration of only one aspect can be misleading. Key conclusions from this study are

1. Refurbishment and variable-speed pumping can improve the overall sustainability of a pump by reducing lifecycle costs, and more so energy consumption and GHG emissions. The overall effect of these two factors is more pronounced when combined;
2. Manufacturing and operation, and maintenance to a lesser degree, represent the largest components of a WDS pump's NPV LCC, wheras operation alone represents an even larger component of energy consumption and GHG emissions. Pump testing, refurbishment costs, and EOL disposal are negligible; and
3. The planning period, target volume, electricity cost, and discount rate are the most sensitive parameters. The present value cost and energy consumption sustainability measures exhibit different levels of sensitivity due to the time value of money.

To the authors' knowledge, there are no comprehensive studies of pump performance and efficiency deterioration over time, nor baseline input data for deterioration models. Despite this, the deterioration model used in this study was calibrated using field data and is advantageous in that it considers both hydraulic performance and energy efficiency deterioration. Regarding future work, there are two key areas of study: (1) develop reference values for pump deterioration models and (2) conduct a comprehensive field investigation of pump deterioration.

Acknowledgments

The authors would like to thank the three anonymous reviewers whose comments helped elevate the quality and content of this article, as well as the Natural Sciences and Engineering Research Council and HydraTek & Associates for their financial support. The authors would also like to thank HydraTek & Associates for providing field data for the example WDS pump.

References

Beebe, R. (2004). "Pump performance and the effect of wear." Chapter 2, *Predictive maintenance of pumps using condition monitoring*, Elsevier B.V., Oxford, U.K., 21–34.

Brion, L., and Mays, L. (1991). "Methodology for optimal operation of pumping stations in water distribution systems." *J. Hyd. Eng.*, 10.1061/(ASCE)0733-9429(1991)117:11(1551), 1551–1569.

Burton, F. (1996). "Water and wastewater industries: Characteristics and energy management opportunities." *Rep. CR-106941*, Electric Power Research Institute, Palo Alto, CA.

Carnegie Mellon. (2014). "Economic input-output life cycle assessment (EIO-LCA), US 2002 purchaser model." Green Design Institute, ⟨http://www.eiolca.net/cgi-bin/dft/use.pl⟩ (Oct. 4, 2014).

Dandy, G., Roberts, A., Hewitson, C., and Chrystie, P. (2008). "Sustainability objectives for the optimization of water distribution networks." *Proc., 8th Annual Water Distribution Systems Analysis Symp.*, ASCE, Reston, VA.

Dennison, F., Azapagic, A., Clift, R., and Colbourne, J. (1999). "Life cycle assessment: Comparing strategic options for the mains infrastructure. Part 1." *J. Water Sci. Technol.*, 39(10–11), 315–319.

Du, F., Woods, G., Kang, D., Lansey, K., and Arnold, R. (2013). "LCA for water and wastewater pipe materials." *J. Environ. Eng.*, 10.1061/(ASCE)EE.1943-7870.0000638, 703–711.

Electric Power Research Institute. (2002). "Water and sustainability (volume 4): U.S. electricity consumption for water supply and treatment—the next half century." *Technical Rep. 1006787*, Palo Alto, CA.

Environment Canada. (2011). "National inventory report– greenhouse gas sources and sinks in Canada." Gatineau, QC.

Filion, Y., MacLean, H., and Karney, B. (2004). "Life-cycle energy analysis of a water distribution system." *J. Infrastruct. Syst.*, 10.1061/(ASCE)1076-0342(2004)10:3(119), 120–130.
Flowserve. (2013). "Worthington LNN, LNNV, and LNNC centrifugal pumps: User instructions." Irving, TX.
Herstein, L., Filion, Y., and Hall, K. (2009). "Evaluating environmental impact in water distribution system design." *J. Infrastruct. Syst.*, 10.1061/(ASCE)1076-0342(2009)15:3(241), 241–250.
HydraTek & Associates. (2013). "Toward municipal sector conservation: A pump efficiency assessment and awareness pilot study." Toronto.
Johnson, J., Reck, B., and Graedel, T. (2008). "The energy benefit of stainless steel recycling." *Energy Policy J.*, 36(1), 181–192.
Kurek, W., and Ostfeld, A. (2013). "Multi-objective optimization of water quality, pumps operation, and storage sizing of water distribution systems." *J. Environ. Manage.*, 115, 189–197.
Lundie, S., Peters, G. M., and Beavis, P. (2004). "Life cycle assessment for sustainable metropolitan water systems planning." *Environ. Sci. Technol.*, 38(13), 3465–3473.
Mala-Jetmarova, H., Barton, A., and Bagirov, A. (2014). "Exploration of the trade-offs between water quality and pumping costs in optimal operating of regional multiquality water distribution systems." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000472, 04014077.
Ontario Ministry of Finance. (2013). "Ontario population projections update: III. Projection results." ⟨http://www.fin.gov.on.ca/en/economy/demographics/projections/projections2012-036.pdf⟩ (Nov. 14, 2013).
Ormsbee, L., and Lansey, K. (1994). "Optimal control of water supply pumping systems." *J. Water Resour. Plann Manage*, 10.1061/(ASCE)0733-9496(1994)120:2(237), 237–252.
Ormsbee, L., Walski, T., Chase, D., and Sharp, W. (1989). "Methodology for improving pump operation efficiency." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)0733-9496(1989)115:2(148), 148–164.
Ostfeld, A., Oliker, N., and Salomons, E. (2013). "Multiobjective optimization for least cost design and resiliency of water distribution systems." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000407, 04014037.
Pascual, R., Rey, P., Hodkiewicz, M., and Cruz, C. (2011). "Integrated model for optimizing strategic overhaul planning of distributed pump stations." *J. Comput. Civ. Eng.*, 10.1061/(ASCE)CP.1943-5487.0000085, 275–282.
Racoviceanu, A., Karney, B., Kennedy, C., and Colombo, A. (2007). "Life-cycle energy use and greenhouse gas emissions inventory for water treatment systems." *J. Infrastruct. Syst.*, 10.1061/(ASCE)1076-0342(2007)13:4(261), 261–270.
Richardson, S., and Hodkiewicz, M. (2011). "Modeling tool to support budgeting and planning decisions for pump overhauls." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000124, 327–334.
Siemens Building Technologies. (2013). "Sizing and selection of butterfly valves." Buffalo Grove, IL.
Stokes, J., and Horvath, A. (2006). "Life cycle energy assessment of alternative water supply systems." *Int. J. LCA*, 11(5), 335–343.
Stokes, J., and Horvath, A. (2011). "Life-cycle assessment of urban water provision: Tool and case study in California." *J. Infrastruct. Syst.*, 10.1061/(ASCE)IS.1943-555X.0000036, 15–24.
Valmatic. (1999). "Flow characteristics of series 2000 butterfly valves, drawing SS-1636." Valve and Manufacturing Corp., Elmhurst, IL.
Wu, W., Maier, H., and Simpson, A. (2013). "Multiobjective optimization of water distribution systems accounting for economic cost, hydraulic reliability, and greenhouse gas emissions." *Water Resour. Research*, 49(3), 1211–1225.
Wu, W., Simpson, A. R., and Maier, H. R. (2010a). "Accounting for greenhouse gas emissions in multiobjective genetic algorithm optimization of water distribution systems." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000020, 146–155.
Wu, W., Simpson, A. R., and Maier, H. R. (2010b). "Single-objective versus multiobjective optimization of water distribution systems accounting for greenhouse gas emissions by carbon pricing." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000072, 555–565.